

NBER WORKING PAPER SERIES

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Working Paper 24811  
<http://www.nber.org/papers/w24811>

NATIONAL BUREAU OF ECONOMIC RESEARCH  
1050 Massachusetts Avenue  
Cambridge, MA 02138  
July 2018

Prepared for the Journal of Economic Perspectives. We are grateful for the comments of Olivier Blanchard, Robert Gordon, Narayana Kocherlakota, Douglas Laxton, Edward Nelson, Giorgio Primiceri and Sergio Rebelo on an earlier draft of this paper. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

At least one co-author has disclosed a financial relationship of potential relevance for this research. Further information is available online at <http://www.nber.org/papers/w24811.ack>

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NBER Working Paper No. 24811

July 2018

JEL No. E0,E3

### **ABSTRACT**

The outcome of any important macroeconomic policy change is the net effect of forces operating on different parts of the economy. A central challenge facing policy makers is how to assess the relative strength of those forces. Dynamic Stochastic General Equilibrium (DSGE) models are the leading framework that macroeconomists have for dealing with this challenge in an open and transparent manner. This paper reviews the state of DSGE models before the financial crisis and how DSGE modelers responded to the crisis and its aftermath. In addition, we discuss the role of DSGE models in the policy process.

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# 1 Introduction

The outcome of any important macroeconomic policy change is the net effect of forces operating on different parts of the economy. A central challenge facing policy makers is how to assess the relative strength of those forces. Economists have a range of tools that can be used to make such assessments. Dynamic stochastic general equilibrium (DSGE) models are the leading tool for making such assessments in an open and transparent manner.

To be concrete, suppose we are interested in understanding the effects of a *systematic* change in policy, like switching from inflation targeting to price-level targeting. The most compelling strategy would be to do randomized control trials on actual economies. But, that course of action is not available to us. So, what are the alternatives? It is certainly useful to study historical episodes in which such a similar policy switch occurred or to use reduced-form time series methods. But, there are obvious limitations to each of these approaches. In the historical approach, the fact that no two episodes are exactly the same always raises questions about the relevance of a past episode for the current situation. In the case of reduced-form methods, it is not always clear which parameters should be changed and which should be kept constant across policy options. Inevitably, assessing the effects of a systematic policy change has to involve the use of a model.

To be useful for policy analysis, DSGE models must be data based. As a practical matter, macroeconomic data aren't sufficient for discriminating between many alternative models that offer different answers to policy questions. Put differently, many DSGE models are observationally equivalent with respect to macro data. But modern DSGE models are based on microeconomic foundations. So, microeconomic data and institutional facts can be brought to bear on the design, construction and evaluation of DSGE models. Micro data break the observational equivalence that was the bane of macroeconomists.

The openness and transparency of DSGE models is a virtue. But it also makes them easy to criticize. Suspicious assumptions can be highlighted. Inconsistencies with the evidence can easily be spotted. Forces that are missing from the model can be identified. The process of responding to informed criticisms is a critical part of the process of building better DSGE models. Indeed, the transparent nature of DSGE models is exactly what makes it possible for diverse groups of researchers - including those who don't work on DSGE models - to be part of the DSGE project.

Some analysts object to working with DSGE models and prefer to instead think about policy by working with small equilibrium models that emphasize different subsets of the economy, labor or financial markets. This approach has a vital contribution to make because small models help us build intuition about the mechanisms at work in DSGE models. But, this approach cannot be a substitute for DSGE models itself because quantitative conclusions about the overall economic impact of a policy requires informal judgment as one integrates across individual small-scale models. The small-model approach to policy thus involves implicit assumptions and lacks the transparency of the DSGE approach.

To be clear, policy decisions are made by real people using their best judgment. Used wisely, DSGE models can improve and sharpen that judgment. In an ideal world, we will have both wise policymakers and empirically plausible models. But, to rephrase Fischer (2017)'s quoting of Samuelson on Solow: "We'd rather have Stanley Fischer than a DSGE model, but we'd rather have Stanley Fischer with a DSGE model than without one."

In section 2 we review the state of mainstream DSGE models before the financial crisis and the Great Recession. In section 3 we describe how DSGE models are estimated and evaluated. Section 4 addresses the question of why DSGE modelers – like most other economists and policy makers – failed to predict the financial crisis and the Great Recession. Section 5 discusses how DSGE modelers responded to the financial crisis and its aftermath. Section 6 discusses how current DSGE models are actually used by policy makers. Section 7 provides a brief response to criticism of DSGE models, with special emphasis on Stiglitz (2017). Section 7 offers concluding remarks.

## **2 Before the Storm**

In this section we describe early DSGE models and how they evolved prior to the crisis.

### **2.1 Early DSGE Models**

As a practical matter, people often use the term DSGE models to refer to quantitative models of growth or business cycle fluctuations. A classic example of a quantitative DSGE model is the Real Business Cycle (RBC) model associated with Kydland and Prescott (1982) and Long and Plosser (1983). These early RBC models imagined an economy populated by households who participate in perfectly competitive goods, factor and asset markets. These models took the position that fluctuations in aggregate economic activity are an efficient response of the economy to the one source of uncertainty in agents' environment, exogenous technology shocks. The associated policy implications are clear: there is no need for any form of government intervention. In fact, government policies aimed at stabilizing the business cycle are welfare-reducing.

Excitement about RBC models crumbled under the impact of three forces. First, micro data cast doubt on some of the key assumptions of the model. These assumptions include, for example, perfect credit and insurance markets, as well as perfectly frictionless labor markets in which fluctuations in hours worked reflect movements along a given labor supply curve or optimal movements of agents in and out of the labor force (see Chetty et al. (2011)). Second, the models had difficulty in accounting for some key properties of the aggregate data, such as the observed volatility in hours worked, the equity premium, the low co-movement of real wages and hours worked (see Christiano and Eichenbaum (1992) and King and Rebelo (1999)). Open-economy versions of these models also failed to account for key observations such as the cyclical co-movement of consumption and output across countries (see Backus

et al. (1992)) and the extremely high correlation between nominal and real exchange rates (see Mussa (1986)).

Third, because money plays no role in RBC models, those models seem inconsistent with mainstream interpretations of various historical episodes. One example is Hume (1742)'s description of how money from the New World affected the European economy. A different example is the view that the earlier a country abandoned the Gold Standard during the Great Depression, the sooner its recovery began (see Bernanke (1995)). A final example is the view that the severity of the U.S. recession in the early 1980s was in large part caused by monetary policy.

Finally, the simple RBC model is effectively mute on a host of policy-related questions that are of vital importance to macroeconomists and policy makers. Examples include: what are the consequences of different monetary policy rules for aggregate economic activity, what are the effects of alternative exchange rate regimes, and what regulations should we impose on the financial sector?

## 2.2 New Keynesian Models

Prototypical pre-crisis DSGE models built upon the chassis of the RBC model to allow for nominal frictions, both in labor and goods markets. These models are often referred to as New Keynesian DSGE models. But, it would be just as appropriate to refer to them as Friedmanite DSGE models. The reason is that they embody the fundamental world view articulated in Friedman's seminal Presidential Address (see Friedman (1968)). According to this view, hyperinflations aside, monetary policy has essentially no impact on real variables like output and the real interest rate in the long run. However, due to sticky prices and wages monetary policy matters in the short run.<sup>1</sup> Specifically, a policy-induced transitory fall in the nominal interest rate is associated with a decline in the real interest rate, an expansion in economic activity and a moderate rise in inflation.

Models in which permanent changes in monetary policy induce roughly one-to-one changes in inflation and the nominal rate of interest are said to satisfy the Fisherian property. Models in which transitory changes in monetary policy induce movements in nominal interest rates and inflation of the opposite sign are said to satisfy the anti-Fisherian property. The canonical New Keynesian models of Yun (1996) and Clarida et al. (1999) and Woodford (2003) satisfy both properties.

The basic intuition behind the anti-Fisherian property of the New Keynesian model is as

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<sup>1</sup> For example, Friedman (1968, p. 10) writes that after the monetary authority increases money growth, "... much or most of the rise in income will take the form of an increase in output and employment rather than in prices. People have been expecting prices to be stable, and prices and wages have been set for some time in the future on that basis. It takes time for people to adjust to a new state of demand. Producers will tend to react to the initial expansion in aggregate demand by increasing output, employees by working longer hours, and the unemployed, by taking jobs now offered at former nominal wages."

follows. Firms set their prices on the basis of current and future marginal costs. The future state of the economy is relatively unaffected by a transitory monetary policy shock. So, actual inflation responds relatively little to a policy induced transitory fall in the nominal interest rate. As a result, the real interest rate declines. Intertemporal substitution by households then induces a rise in current consumption, leading to a rise in labor income. That increase reinforces the contemporaneous rise in consumption and employment. The expansion in employment drives wages and marginal costs up. The latter effect drives inflation up. Since inflation and the nominal interest move in opposite directions, the model has the anti-Fisherian property. Less surprisingly, standard New Keynesian models satisfy the Fisherian property because its long-run properties are roughly the same as the underlying RBC chassis.

Many researchers found New Keynesian models attractive because they seemed sensible and they allowed researchers to engage in the types of policy debates that RBC models had been silent about. A critical question was: what properties should quantitative versions of these models have? To address this question, the empirical literature focused on quantifying the dynamic effects of a shock to monetary policy. This type of shock has long been of interest to macroeconomists for a variety of reasons. For example, Friedman and Schwartz (1963) attributed the major portion of business cycle variations to exogenous shocks in the money supply. The recent literature finds these shocks interesting because they provide a potentially powerful diagnostic for discriminating between models. Perhaps the most extreme example is that a real business cycle model implies nothing happens to real variables after a monetary policy shock. In contrast, simple New Keynesian models imply that real variables do respond to a monetary policy shock.

A monetary policy shock can reflect a variety of factors including measurement error in the real-time data that policy makers condition their actions on and the basic randomness that is inherent in group decisions. In a seminal paper Sims (1986) argued that one should identify monetary policy shocks with disturbances to a monetary policy reaction function in which the policy instrument is a short-term interest rate. Bernanke and Blinder (1992) and Christiano et al. (1996, 1999) identify monetary policy shocks using the assumption that monetary policy shocks have no contemporaneous impact on inflation and output.<sup>2</sup> This set of identifying restrictions, like the entire New Keynesian enterprise, falls squarely in the Friedman world view. For example, in testimony before Congress, Friedman (1959) said:

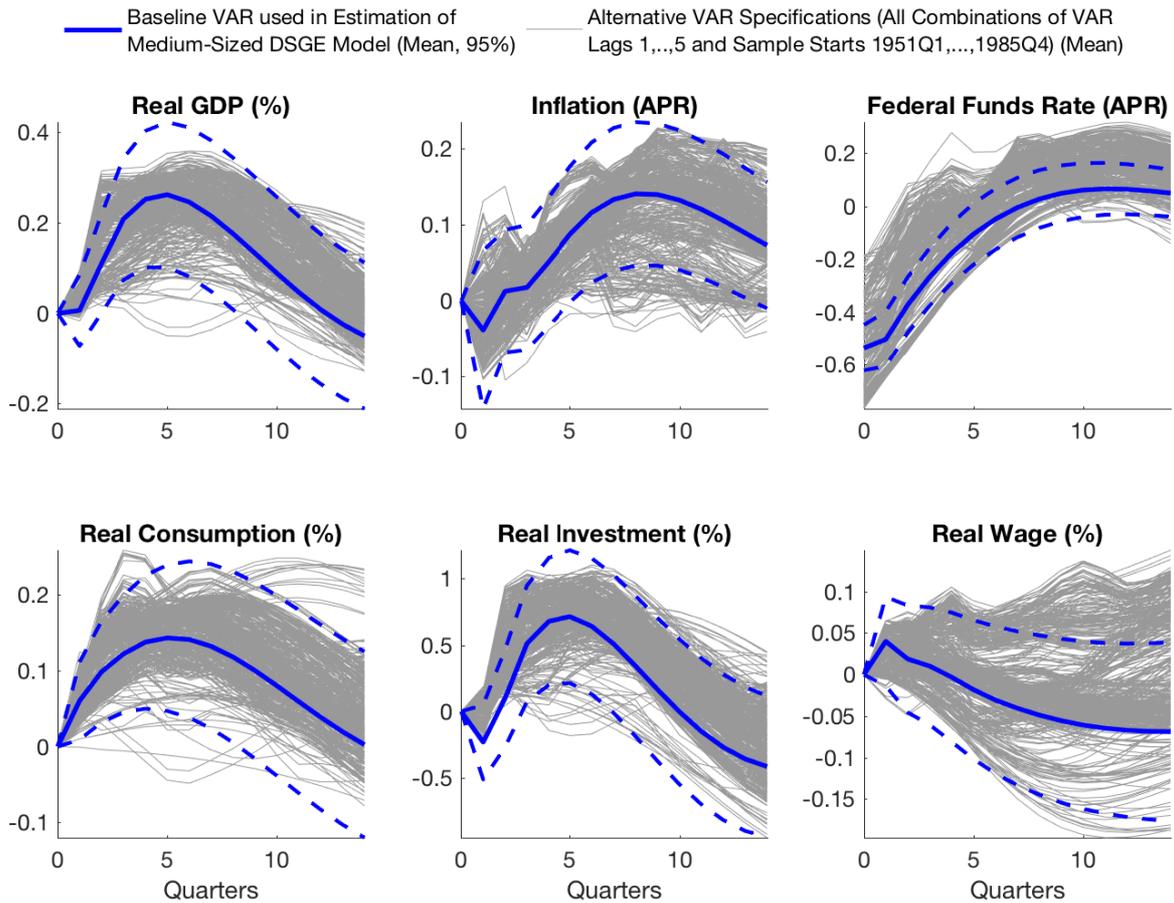
“Monetary and fiscal policy is rather like a water tap that you turn on now and that then only starts to run 6, 9, 12, 16 months from now.”

In practice, this Friedman-style identifying strategy is implemented using a vector autoregression representation (VAR) with a large set of variables. Figure 1, taken from Christiano, Trabandt and Walentin (2010), displays the effects of identified monetary policy shocks estimated using data covering the period 1951Q1 to 2008Q4. For convenience we only show the response functions for a subset of the variables in the VAR. The dashed lines correspond to 95% confidence intervals about the point estimates (solid black line).

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<sup>2</sup> Christiano, Eichenbaum and Evans (1999) show that the results from imposing this assumption on monthly or quarterly data are qualitatively similar. The assumption is obviously more compelling for monthly data.

Figure 1: VAR Impulse Responses to a Monetary Policy Shock



Notes: All data are expressed in deviations from what would have happened in the absence of the shock. The units are given in the titles of the subplots. % means percent deviation from unshocked path. APR means annualized percentage rate deviation from unshocked path.

Overall, the results are consistent with the view that an expansionary monetary policy shock has the effects that Friedman (1968) asserted in his Presidential Address. Specifically, an expansionary monetary policy shock corresponding to a decline in the U.S. federal funds rate leads to hump-shaped expansions in consumption, investment and output, as well as relatively small rises in real wages and inflation. Since the inflation rate moves very little in response to a monetary policy shock, the responses in the real interest rate and the federal funds rate are roughly the same.

A natural question is how robust the results in Figure 1 are to the various technical assumptions underlying the statistical analysis. Here, we focus on sensitivity to the number of lags in the VAR and to the start of the sample period. A VAR represents each variable as a function of the lagged values of all the variables in the system. Denote the number of lags by  $n$ . The baseline specification in Figure 1 assumes  $n=2$ . The Figure reports the results of redoing the analysis for  $n=1, \dots, 5$ . For each value of  $n$ , the Figure reports the results based on starting the sample period in each of the dates 1951Q1, 1951Q2, ..., 1985Q4. In this way, we generate 700 sets of results, each of which is displayed by a thin solid grey line in Figure 1. Note that the basic qualitative properties of the benchmark analysis are remarkably robust, although there are of course

specifications of  $n$  and the sample period that yield different implications. It is interesting how similar the shape of the confidence and sensitivity intervals are.

In recent years researchers have developed alternative procedures for identifying monetary policy shocks. These procedures focus on movements in the federal funds futures rate in a tight window of time around announcements made by monetary policy makers. See, for example, Gertler and Karadi (2015) who build on the work of Kuttner (2001) and Gürkaynak, Sack and Swanson (2005). Broadly speaking, this literature reaches the same conclusions about the effects of monetary policy shocks displayed in Figure 1. In our view, these conclusions summarize the conventional view about the effects of a monetary policy shock.

## **2.3 Christiano, Eichenbaum and Evans' Model**

A key challenge was to develop an empirically plausible version of the New Keynesian model that could account quantitatively for the type of impulse response functions displayed in Figure 1. Christiano et al. (2005) developed a version of the New Keynesian model that met this challenge. We go into some detail describing the basic features of that model because they form the core of leading pre-crisis DSGE models, such as Smets and Wouters (2003, 2007).

### **2.3.1 Consumption and Investment Decisions**

Consistent with a long tradition in macroeconomics, the model economy in Christiano et al. (2005) is populated by a representative household. At each date, the household allocates money to purchases of financial assets, as well as consumption and investment goods. The household receives income from wages, from renting capital to firms and from financial assets, all net of taxes.

As in the simple New Keynesian model, Christiano et al. (2005) make assumptions that imply the household's borrowing constraints are not binding. So, the interest rate determines the intertemporal time pattern of consumption. Of course, the present value of income determines the level of consumption. Holding interest rates constant, the solution to the household problem is consistent with a key prediction of Friedman's permanent income hypothesis: persistent changes in income have a much bigger impact on household consumption than transitory changes.

To be consistent with the response of consumption and the interest rate to a monetary policy shock observed in Figure 1, Christiano et al. (2005) had to depart from the standard assumption that utility is time-separable in consumption. Generally speaking, that assumption implies that after a policy-induced decline in the interest rate, consumption jumps immediately and then falls. But, this is a very different pattern than the hump-shape response that we see in Figure 1. To remedy this problem, Christiano et al. (2005) follow Fuhrer (2000) by adopting the assumption of habit-formation in consumption. Under this specification, the marginal utility of current consumption depends positively on the level of

the household's past consumption. Households then choose to raise consumption slowly over time, generating a hump-shape response-pattern as in Figure 1. As it turns out, there is substantial support for habit persistence in the finance, growth and psychology literatures.<sup>3</sup>

To be consistent with the hump-shape response of investment to a monetary policy shock, Christiano et al. (2005) had to assume households face costs of changing the rate of investment. To see why, note that absent uncertainty, arbitrage implies that the one-period return on capital is equal to the real rate of interest on bonds. Absent any adjustment costs, the one-period return on capital is the sum of the marginal product of capital plus one minus the depreciation rate. Suppose that there is an expansionary monetary policy shock that drives down the real interest rate, with the maximal impact occurring contemporaneously, as in the data (see Figure 1). Absent adjustment costs, arbitrage requires that the marginal product of capital follow a pattern identical to the real interest rate. For that to happen both the capital stock and investment must have exactly the opposite pattern than the marginal product of capital. With the biggest surge in investment occurring in the period of the monetary policy shock the simple model cannot reproduce the hump-shape pattern in Figure 1. When it is costly to adjust the rate of investment, households choose to raise investment slowly over time, generating a hump-shape response-pattern as in Figure 1.

Lucca (2006) and Matsuyama (1984) provide interesting theoretical foundations for the investment adjustment cost in Christiano et al. (2005). In addition, there is substantial empirical evidence in support of the specification (see Eberly et al. (2012) and Matsuyama (1984)).

An important alternative specification of adjustment costs penalizes changes in the capital stock. This specification has a long history in macroeconomics, going back at least to Lucas and Prescott (1971). Christiano, Eichenbaum and Evans show that with this type of adjustment cost, investment jumps after an expansionary monetary policy shock and then converges monotonically back to its pre-shock level from above. This response pattern is inconsistent with the VAR evidence.

### **2.3.2 Nominal Rigidities**

In contrast to RBC models, goods and labor markets in Christiano et al. (2005) are not perfectly competitive. This departure is necessary to allow for sticky prices and sticky nominal wages – if a price or wage is sticky, someone has to set it.

In Christiano et al. (2005), nominal rigidities arise from Calvo (1983) style frictions. In particular, firms and households can change prices or wages with some exogenous

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<sup>3</sup> In the finance literature see, for example, Eichenbaum and Hansen (1990), Constantinides (1990) and Boldrin et al. (2001). In the growth literature see Carroll et al. (1997, 2000). In the psychology literature, see Gremel et al. (2016).

probability. In addition, they must satisfy whatever demand materializes at those prices and wages.

Calvo-style frictions make sense only in environments where inflation is moderate. Even in moderate inflation environments, Calvo-style frictions have implications that are inconsistent with aspects of micro data (see for example Nakamura and Steinsson (2008) or Eichenbaum et al. (2011)). Still, its continued use reflects two factors. First, Calvo-style frictions allow models to capture, in an elegant and tractable manner, what many researchers believe is an essential feature of business cycles: for moderate inflation economies, firms and labor suppliers typically respond to variations in demand by varying quantities rather than prices. Second, authors like Eichenbaum et al. (2011) argue that, for moderate inflation economies, the Calvo model provides a good approximation to more plausible models in which firms face costs of changing their pricing strategies.

### **2.3.3 A-cyclical Marginal Costs**

Christiano et al. (2005) build features into the model which ensure that firms' marginal costs are nearly a-cyclical. They do so for three reasons. First, there is substantial empirical evidence in favor of this view (see for example, Anderson et al. (2018)). Second, the more a-cyclical marginal cost is, the more plausible is the assumption that firms satisfy demand. Third, as in standard New Keynesian models, inflation is an increasing function of current and expected future marginal costs. So, relatively a-cyclical marginal costs are critical for dampening movements in the inflation rate.

The model in Christiano et al. (2005) incorporates two mechanisms to ensure that marginal costs are relatively a-cyclical. The first is the sticky nominal wage assumption mentioned above. The second mechanism is that the rate at which capital is utilized can be varied in response to shocks.

### **2.3.4 Quantitative Properties**

To illustrate the model's quantitative properties, we work with the variant of the model of Christiano et al. (2005) estimated by Christiano, Eichenbaum and Trabandt (2016). We re-estimated the model using a Bayesian procedure that treats the VAR-based impulse responses to a monetary policy shock as data. The appendix to this paper provides details about the prior and posterior distributions of model parameters. Here we highlight some of the key estimated parameters. The posterior mode estimates imply that firms change prices on average once every 2.3 quarters, the household changes nominal wages about once a year, past consumption enters with a coefficient of 0.75 in the household's utility function, and the elasticity of investment with respect to a one percent temporary increase in the current price of installed capital is equal to 0.16.

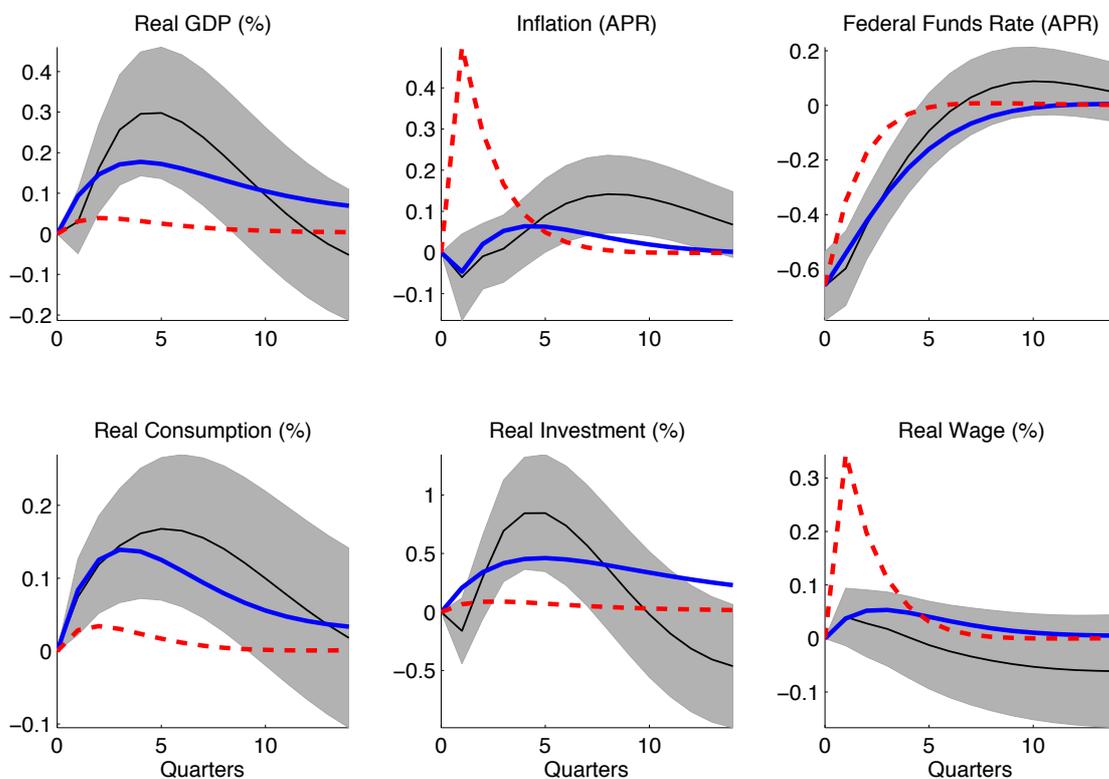
The thin solid black lines in Figure 2 are the VAR-based impulse response function estimates reproduced from Figure 1. The grey area depicts the 95% confidence intervals associated with

those estimates. The solid blue line depicts the impulse response function of the estimated DSGE model to a monetary policy shock, calculated using the mode of the posterior distribution of the model's parameters.

Four key features of the results are worth noting. First, the model succeeds in accounting for the hump-shaped rise in consumption, investment and real GDP after a policy-induced fall in the federal funds rate. Second, the model succeeds in accounting for the small rise in inflation after the shock. Third, the model has the property that real wages are essentially unaffected by the policy shock. Finally, the model has the anti-Fisherian property that the nominal interest and inflation move in the opposite direction after a transitory monetary policy shock.

Figure 2: Impulse Responses to a Monetary Policy Shock -- VAR vs. Model

■ VAR 95% — VAR Mean — Estimated CET (2016) Model with Sticky Wages - - - Model with Flexible Wages



Notes: All data are expressed in deviations from what would have happened in the absence of the shock. The units are given in the titles of the subplots. % means percent deviation from unshocked path. APR means annualized percentage rate deviation from unshocked path.

We emphasize that the model's properties depend critically on sticky wages. The red dashed line in Figure 2 depicts the model's implications if we recalculate the impulse responses assuming that nominal wages are fully flexible (holding other model parameters fixed at the mode of the posterior distribution). Note that the model's performance deteriorates drastically.

In Christiano, Eichenbaum and Evans (2005), sticky wages are sticky by assumption. Christiano, Eichenbaum and Trabandt (2016) show that wage stickiness arises endogenously in a version of Christiano, Eichenbaum and Evans (2005), where there are labor market search and matching frictions. The key feature of the model is that workers and firms bargain in a way that reduces the sensitivity of the wage to macroeconomic aggregates. One advantage of endogenously generating sticky wages in this way is that Christiano, Eichenbaum and Trabandt (2016) can analyze the aggregate effects of various policies like unemployment insurance.

Finally, we note that habit formation and investment adjustment costs are critical to the model's success. Absent those features, it would be very difficult to generate hump-shaped responses with reasonable degrees of nominal rigidities.

### **3 How DSGE Models Are Estimated and Evaluated**

Prior to the financial crisis, researchers generally worked with log-linear approximations to the equilibria of DSGE models. There were three reasons for this choice. First, for the models being considered and for the size of shocks that seemed relevant for the post-war U.S. data, linear approximations are very accurate (see for example the papers in Taylor and Uhlig (1990)). Second, linear approximations allow researchers to exploit the large array of tools for forecasting, filtering and estimation provided in the literature on linear time series analysis. Third, it was simply not computationally feasible to solve and estimate large, nonlinear DSGE models. The technological constraints were real and binding.

Researchers choose values for the key parameters of their models using a variety of strategies. In some cases, researchers choose parameter values to match unconditional model and data moments, or they reference findings in the empirical micro literature. This procedure is called calibration and does not use formal sampling theory. Calibration was the default procedure in the early RBC literature and it is also sometimes used in the DSGE literature. Most of the modern DSGE literature conducts inference about parameter values and model fit using one of two strategies that make use of formal econometric sampling theory.

The first strategy is limited information because it does not exploit all of the model's implications for moments of the data. One variant of the strategy minimizes the distance between a subset of model-implied second moments and their analogs in the data. A more influential variant of this first strategy estimates parameters by minimizing the distance between model and data impulse responses to economic shocks (examples of the impulse response matching approach include Christiano et al. (2005), Altig et al. (2011), Iacoviello (2005) and Rotemberg and Woodford (1991)).

One way to estimate the data impulse response functions is based on partially identified VARs. Another variant of this strategy, sometimes referred to as the method of external instruments, involves using historical or narrative methods to obtain instruments for the

underlying shocks (see, Mertens and Ravn (2013)). Finally, researchers have exploited movements in asset prices immediately after central bank policy announcements to identify monetary policy shocks and their consequences. This approach is referred to as high frequency identification (early contributions include e.g. Kuttner (2001) and Gürkaynak et al. (2005)).

The initial limited information applications in the DSGE literature used generalized method of moments estimators and classical sampling theory (see Hansen (1982)). Building on the work of Chernozhukov and Hong (2003), Christiano et al. (2010) showed how the Bayesian approach can be applied in limited information contexts.

A critical advantage of the Bayesian approach is that one can formally and transparently bring to bear information from a variety of sources on what constitutes “reasonable” values for model parameters. Suppose, for example, that one could only match the dynamic response to a monetary policy shock for model parameter values implying that firms change their prices on average every two years. This implication is strongly at variance with evidence from micro data. In the Bayesian approach, the analyst would impose priors that sharply penalize such parameter values so that those parameter values would be assigned low probabilities in the analyst’s posterior distribution. Best practice compares priors and posteriors for model parameters. This comparison allows the analyst to make clear the role of priors and the data in generating the results.

As we just stressed the Bayesian approach allows one to bring to bear information culled from micro data on model parameters. This approach allows one to bring to bear information culled from micro data on model parameters. At a deeper level, micro data influences, in a critical but slow-moving manner, the class of models that we work with. Our discussion of the demise of the pure RBC model is one illustration of this process. The models of financial frictions and heterogeneous agents discussed below are an additional illustration of how DSGE models evolve over time in response to micro data (see sections 5.1 and 5.3).

The second strategy for estimating DSGE models involves full-information methods. In many applications, the data used for estimation is relatively uninformative about the value of some of the parameters in DSGE models (see Canova and Sala (2009)). A natural way to deal with this fact is to bring other information to bear on the analysis. Bayesian priors are a vehicle for doing exactly that. This is an important reason why the Bayesian approach has been very influential in full-information applications. Starting from Smets and Wouters (2003), a large econometric literature has expanded the Bayesian toolkit to include better ways to conduct inference about model parameters and to analyze model fit. For a recent survey see Fernandez-Villaverde et al. (2016).

## 4 Why Didn't DSGE Models Predict the Financial Crisis?

Pre-crisis DSGE models didn't predict the increasing vulnerability of the U.S. economy to a financial crisis. They have also been criticized for not placing more emphasis on financial frictions. Here, we give our perspective on these failures.

There is still an ongoing debate about the causes of the financial crisis. Our view, shared by Bernanke (2009) and many others, is that the financial crisis was precipitated by a rollover crisis in a very large and highly levered shadow-banking sector that relied on short-term debt to fund long-term assets. By shadow banks we mean financial institutions not covered by the protective umbrella of the Federal Reserve and Federal Deposit Insurance Corporation (for further discussion, see Bernanke (2010)).

Rollover crisis was triggered by a set of developments in the housing sector. U.S. housing prices began to rise rapidly in the 1990's. The S&P/Case-Shiller U.S. National Home Price Index rose by a factor of roughly 2.5 between 1991 and 2006. The precise role played by expectations, the subprime market, declining lending standards in mortgage markets, and overly-loose monetary policy is not critical for our purposes. What is critical is that housing prices began to decline in mid-2006, causing a fall in the value of the assets of shadow banks that had heavily invested in mortgage-backed securities. The Fed's willingness to provide a safety net for the shadow banking system was at best implicit, creating the conditions under which a roll-over crisis was possible. In fact, a rollover crisis did occur and shadow banks had to sell their asset-backed securities at fire-sale prices, precipitating the financial crisis and the Great Recession.

Against this background, we turn to the first of the two criticisms of DSGE models mentioned above, namely their failure to signal the increasing vulnerability of the U.S. economy to a financial crisis. This criticism is correct. The failure reflected a broader failure of the economics community. The overwhelming majority of academics, regulators and practitioners did not realize that a small shadow-banking system had metastasized into a massive, poorly-regulated, wild west-like sector that was not protected by deposit insurance or lender-of-last-resort backstops.

We now turn to the second criticism of DSGE models, namely that they did not sufficiently emphasize financial frictions. In practice modelers have to make choices about which frictions to emphasize. One reason why modelers did not emphasize financial frictions in DSGE models is that until the Great Recession, post-war recessions in the U.S. and Western Europe did not seem closely tied to disturbances in financial markets. The Savings and Loans crisis in the US was a localized affair that did not grow into anything like the Great Recession. Similarly, the stock market meltdown in 1987 and the bursting of the tech-bubble in 2001 only had minor effects on aggregate economic activity.

At the same time, the financial frictions that were included in DSGE models did not seem to

have very big effects. Consider, for example, Bernanke et al. (1999)'s influential model of the financial accelerator. That model is arguably the most influential pre-crisis DSGE model with financial frictions. It turns out that the financial accelerator has only a modest quantitative effect on the way the model economy responds to shocks, see e.g. Lindé et al. (2016). In the same spirit, Kocherlakota (2000) argues that models with Kiyotaki and Moore (1997) type credit constraints have only negligible effects on dynamic responses to shocks. Finally, Brzoza-Brzezina and Kolasa (2013) compare the empirical performance of the standard New Keynesian DSGE model with variants that incorporate Kiyotaki and Moore (1997) and Bernanke et al. (1999) type constraints. Their key finding is that neither model substantially improves on the performance of the benchmark model, either in terms of marginal likelihoods or impulse response functions. So, guided by the post-war data from the U.S. and Western Europe, and experience with existing models of financial frictions, DSGE modelers emphasized other frictions.

## 5 After the Storm

Given the data-driven nature of DSGE enterprise, it is not surprising that the financial crisis and its aftermath had an enormous impact on DSGE models. In this section we discuss the major strands of work in post-financial crisis DSGE models.

### 5.1 Financial Frictions

The literature on financial frictions can loosely be divided between papers that focus on frictions originating inside financial institutions and those that arise from the characteristics of the people who borrow from financial institutions. Theories of bank runs and rollover crisis focus on the first class of frictions. Theories of collateral constrained borrowers focus on the second class of frictions. We do not have space to systematically review the DSGE models that deal with both types of financial frictions. Instead, we discuss examples of each.

#### *Frictions That Originate Inside Financial Institutions*

Motivated by events associated with the financial crisis, Gertler and Kiyotaki (2015) and Gertler, Kiyotaki and Prestipino (2016) develop a DSGE model of a rollover crisis in the shadow banking sector, which triggers fire sales. The resulting decline in asset values tightens balance sheet constraints in the rest of the financial sector and throughout the economy.<sup>4</sup>

In the Gertler and Kiyotaki (2015) model, shadow banks finance the purchase of long-term assets by issuing short-term (one-period) debt. Banks have two ways to deal with short-term debt that is coming due. The first is to issue new short-term debt (this is called rolling over

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<sup>4</sup> The key theoretical antecedent is the bank run model of Diamond and Dybvig (1983) and the sovereign debt rollover crisis model of Cole and Kehoe (2000).

the debt). The second is to sell assets. The creditor’s only decision is whether or not to buy new short-term debt. There is nothing the creditor can do to affect payments received on past short-term debt. Unlike in the classic bank run model of Diamond and Dybvig (1983), there is no reason to impose a sequential debt service constraint.

There is always an equilibrium in the Gertler and Kiyotaki (2015) model in which shadow banks can roll over the short-term debt without incident. But, there can also be an equilibrium in which each creditor chooses not to roll over the debt. Suppose that an individual creditor believes that all other creditors won’t extend new credit to banks. In that case, there will be a system- wide failure of the banks, as attempts to pay off bank debt lead to fire sales of assets that wipes out bank equity. The individual creditor would prefer to buy assets at fire sale prices rather than extend credit to a bank that has zero net worth. With every potential creditor thinking this way, it is a Nash equilibrium for each creditor to not purchase new liabilities from banks. Such an equilibrium is referred to as a roll over crisis.

A roll over crisis leads to fire sales because, with all banks selling, the only potential buyers are other agents who have little experience evaluating the banks’ assets. In this state of the world, agency problems associated with asymmetric information become important.<sup>5</sup>

Figure 3: Balance Sheet of the Shadow-Banking Sector Before and After the Housing Market Correction: An Illustrative Example

Pre-housing market correction		Post-housing market correction	
Assets	Liabilities	Assets	Liabilities
120 (105)	Deposits: 100	110 (95)	Deposits: 100
	Banker net worth 20 (5)		Banker net worth 10 (-5)

*Note:* Figure 3 captures in a highly stylized way the key features of the shadow-banking system before (left side) and after (right side) the housing crisis. The numbers without parentheses are baseline values, while the numbers in parentheses show what the values would be if there were to be a rollover crisis and fires-sale of assets. In the pre-housing market correction period, the banks would stay solvent in a rollover crisis; therefore no rollover crisis can occur according the analysis of Gertler and Kiyotaki (2015). In the post-housing market correction period, the value of the assets in the case of a rollover crisis is 95 and the net worth of the bank is negative. In this scenario a rollover crisis can occur.

As part of the specification of the model, Gertler and Kiyotaki (2015) assume that the probability of a rollover crisis is proportional to the losses depositors would experience in the event that a rollover crisis occurs. So, if bank creditors think that banks’ net worth would be positive in a crisis, then a rollover crisis is impossible. However, if banks’ net worth is negative in this scenario then a rollover crisis can occur.

<sup>5</sup> Gertler and Kiyotaki (2015) capture these agency problems by assuming that the buyers of long-term assets during a rollover crisis are relatively inefficient at managing the assets.

We use this model to illustrate how a relatively small shock can trigger a system-wide rollover crisis in the shadow banking system. To this end, consider the example Figure 3, which captures in a highly stylized way the key features of the shadow-banking system before (left side) and after (right side) the crisis. In the left-side table the shadow banks' assets and liabilities are 120 and 100, respectively. So, their net worth is positive. The numbers in parentheses show the value of the assets and net worth of the shadow banks if there were to be a rollover crisis and fire-sale of assets. Since net worth remains positive, the Gertler and Kiyotaki analysis implies that a rollover crisis cannot occur.

Now imagine that the assets of the shadow banks decline because of a small shift in fundamentals. Here, we have in mind the events associated with the decline in housing prices that began in the summer of 2006. The right side of Figure 3 is the analog of the left side, taking into account the lower value of the shadow banks' assets. In the example, the market value of assets has fallen by 10, from 120 to 110. In the absence of a rollover crisis, the system is solvent. However, the value of the assets in the case of a rollover crisis is 95 and the net worth of the bank is negative in that scenario. So, a relatively small change in asset values could lead to a severe financial crisis.

The example illustrates two important potential uses of DSGE models. First, an estimated DSGE model can be used to calculate the probability of a roll over crisis, conditional on the state of the economy. In principle, one could estimate this probability function using reduced form methods. However, since financial crises are rare events, estimates emerging from reduced form methods would have enormous sampling uncertainty. Because of its general equilibrium structure, an empirically plausible DSGE model would address the sampling uncertainty problem by making use of a wider array of information drawn from non-crisis times to assess the probability of a financial crisis. The second potential use of DSGE models is to design policies that deal optimally with financial crises. For this task, structure is essential. While we think that existing DSGE models of financial crisis such as Gertler and Kiyotaki yield valuable insights, these models are clearly still in their infancy.

For example, the model assumes that people know what can happen in a crisis, together with the associated probabilities. This seems implausible, given the fact that a full-blown crisis is a two or three times a century event. It seems safe to conjecture that factors such as aversion to 'Knightian uncertainty' play an important role in driving fire sales in a crisis (see, for example, Caballero and Krishnamurthy (2008)). Still, research on various types of crises is proceeding at a rapid pace, and we expect to see substantial improvements in DSGE models on the subject. For an example, see Bianchi et al. (2016) and the references therein.

#### *Frictions Associated with the People that Borrow from Financial Institutions*

We now turn to our second example, which focuses on frictions that arise from the characteristics of the people who borrow from financial institutions. One of the themes of this paper is that data analysis lies at the heart of the DSGE project. Elsewhere, we have stressed the importance of microeconomic data. Here, we also stress the role of financial data as a source of information about the sources of economic fluctuations. Using an estimated

DSGE model, Christiano et al. (2014) argue that the dominant source of U.S. business cycle fluctuations are disturbances in the riskiness of individual firms (what they call risk shocks). A motivation for their analysis is that in recessions, firms pay a premium to borrow money, above the rate at which a risk-free entity like the U.S. government borrows. Christiano et al. (2014) in effect interpret this premium as reflecting the view of lenders that firms represent a riskier bet. Christiano et al. (2014) estimate their DSGE model using a large number of macroeconomic and financial variables and conclude that fluctuations in risk can account for the bulk of GDP fluctuations.

To understand the underlying economics, consider a recession that is triggered by an increase in the riskiness of firms.<sup>6</sup> As the cost of borrowing rises, firms borrow less and demand less capital. This decline induces a fall in both the quantity and price of capital. In the presence of nominal rigidities and a Taylor rule for monetary policy, the decline in investment leads to an economy-wide recession, including a fall in consumption and a rise in firm bankruptcies. With the decline in aggregate demand, inflation falls. Significantly, the risk shock leads to an increase in the cross-sectional dispersion of the rate of return on firm equity. Moreover, the recession is also associated with a fall in the stock market, driven primarily by capital losses associated with the fall in the price of capital. All these effects are observed in a typical recession.<sup>7</sup> This property of risk shocks is why Christiano et al. (2014)'s estimation procedure attributes 60 percent of the variance of U.S. business cycles to them.

The dynamic effects of risk shocks in the Christiano et al. (2014) model resemble business cycles so well, that many of the standard shocks that appear in previous business cycle models are rendered unimportant in the empirical analysis. For example, Christiano et al. (2014) find that aggregate shocks to the technology for producing new capital account for only 13 percent of the business cycle variation in GDP. This contrasts sharply with the results in Justiniano et al. (2010), who argue that this shock accounts for roughly 50 percent of business cycle variation of GDP. The critical difference is that Christiano et al. (2014) include financial data like the stock market in their analysis. Shocks to the supply of capital give rise to countercyclical movements in the stock market, so they cannot be the prime source of business cycles.

Financial frictions have also been incorporated into a growing literature that introduces the housing market into DSGE models. One part of this literature focuses on the implications of housing prices for households' capacity to borrow (see Iacoviello and Neri (2010) and Berger et al. (2017)). Another part focuses on the implications of land and housing prices on firms' capacity to borrow (Liu et al. (2013)). Space constraints prevent us from surveying this literature here.

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<sup>6</sup> In Christiano et al. (2014) a rise in risk corresponds to an increase in the variance of a firm-specific shock to technology. Absent financial frictions, such a shock would have no impact on aggregate output. A rise in the variance would lead to bigger-sized shocks at the firm level but the average across firms is only a function of the mean (law of large numbers).

<sup>7</sup> To our knowledge, the first paper to articulate the idea that a positive shock to idiosyncratic risk could produce effects that resemble a recession is Williamson (1987).

## 5.2 Zero Lower Bound and Other Nonlinearities

The financial crisis and its aftermath was associated with two important nonlinear phenomena. The first phenomenon was the rollover crisis in the shadow-banking sector discussed above. The Gertler and Kiyotaki (2015) model illustrates the type of nonlinear model required to analyze this type of crisis. The second phenomenon was that the nominal interest rate hit the zero-lower bound in December 2008. An earlier theoretical literature associated with Krugman (1998), Benhabib et al. (2001) and Eggertsson and Woodford (2003) had analyzed the implications of the zero-lower bound for the macroeconomy. Building on this literature, DSGE modelers quickly incorporated the zero-lower bound into their models and analyzed its implications.

In what follows, we discuss one approach that DSGE modelers took to understand what triggered the Great Recession and why it persisted for so long. We then review some of the policy advice that emerges from recent DSGE models.

### *The Causes of the Crisis and Slow Recovery*

One set of papers uses detailed nonlinear DSGE models to assess which shocks triggered the financial crisis and what propagated their effects over time. We focus on three papers to give the reader a flavor of this literature. Christiano et al. (2015) analyze the post-crisis period taking into account that the zero lower bound was binding. In addition, they take into account the Federal Reserve Open Market Committee's (FOMC) guidance about future monetary policy. This guidance was highly nonlinear in nature: it involved a regime switch depending on the realization of endogenous variables (e.g. the unemployment rate).

Christiano et al. (2015) argue that the bulk of movements in aggregate real economic activity during the Great Recession was due to financial frictions interacting with the zero-lower bound. At the same time, their analysis indicates that the observed fall in total factor productivity and the rise in the cost of working capital played important roles in accounting for the surprisingly small drop in inflation after the financial crisis.

Lindé and Trabandt (2018b) argue that nonlinearities in price and wage-setting are an alternative reason for the small decline in inflation during the Great Recession. In particular, they assume that the elasticity of demand of a goods-producing firm is increasing in its relative price along the lines proposed in Kimball (1995). So, during a recession when marginal costs are falling, firms that can change their prices have less of an incentive to do so relative to the case in which the elasticity of demand is constant. They show that this effect is quantitatively important in the standard nonlinear New Keynesian DSGE model.

Gust et al. (2017) estimate a fully nonlinear DSGE model with an occasionally binding zero lower bound. Nonlinearities in the model play an important role for inference about the source and propagation of shocks. According to their analysis, shocks to the demand for risk-free bonds and, to a lesser extent, the marginal efficiency of investment proxying for financial frictions, played a critical role in the crisis and its aftermath.

A common feature of the previous papers is that they provide a quantitatively plausible model of the behavior of major economic aggregates during the Great Recession when the zero lower bound was a binding constraint. Critically, those papers include both financial frictions and nominal rigidities. A model of the crisis and its aftermath which didn't have financial frictions just would not be plausible. At the same time, a model that included financial frictions but didn't allow for nominal rigidities would have difficulty accounting for the broad-based decline across all sectors of the economy. Such a model would predict a boom in sectors of the economy that are less dependent on the financial sector.

The fact that DSGE models with nominal rigidities and financial frictions can provide quantitatively plausible accounts of the financial crisis and the Great Recession makes them obvious frameworks within which to analyze alternative fiscal and monetary policies. We begin with a discussion of fiscal policy.

### *Fiscal Policy*

In standard DSGE models, an increase in government spending triggers a rise in output and inflation. When monetary policy is conducted according to a standard Taylor rule that obeys the Taylor principle, a rise in inflation triggers a rise in the real interest rate. Other things equal, the policy-induced rise in the real interest rate lowers investment and consumption demand. So, in these models the government spending multiplier is typically less than one. But when the zero lower bound binds, the rise in inflation associated with an increase in government spending does not trigger a rise in the real interest rate. With the nominal interest rate stuck at zero, a rise in inflation lowers the real interest rate, crowding consumption and investment in, rather than out. This raises the quantitative question: how does a binding zero lower bound constraint on the nominal interest rate affect the size of the government spending multiplier?

Christiano et al. (2011) address this question in a DSGE model, assuming all taxes are lump-sum. A basic principle that emerges from their analysis is that the multiplier is larger the more binding is the zero lower bound. Christiano et al. (2011) measure how binding the zero lower bound is by how much a policymaker would like to lower the nominal interest below zero if he or she could. For their preferred specification, the multiplier is much larger than one. When the ZLB is not binding, then the multiplier would be substantially below one.

Erceg and Lindé (2014) examine among other things the impact of distortionary taxation on the magnitude of government spending multiplier in the zero lower bound. They find that the results based on lump-sum taxation are robust relative to the situation in which distortionary taxes are raised gradually to pay for the increase in government spending.

There is by now a large literature that studies the fiscal multiplier when the ZLB binds using DSGE models that allow for financial frictions, open-economy considerations and liquidity constrained consumers. We cannot review this literature because of space constraints. But, the crucial point is that DSGE models are playing an important role in the debate among academics and policymakers about whether and how fiscal policy should be used to fight

recessions. We offer two examples in this regard. First, Coenen et al. (2012) analyze the impact of different fiscal stimulus shocks in several DSGE models that are used by policy-making institutions. The second example is Blanchard et al. (2017) who analyze the effects of a fiscal expansion by the core euro area economies on the periphery euro area economies. Finally, we note that the early papers on the size of the government spending multiplier use log-linearized versions of DSGE models. For example, Christiano et al. (2011) work with a linearized version of their model while Christiano et al. (2015) work with a nonlinear version of the model. Significantly, there is now a literature that assesses the sensitivity of multiplier calculations to linear versus nonlinear solutions. See, for example, Christiano and Eichenbaum (2012), Boneva et al. (2016), Christiano et al. (2017) and Lindé and Trabandt (forthcoming).

### *Forward Guidance*

When the zero lower bound constraint on the nominal interest rate became binding, it was no longer possible to fight the recession using conventional monetary policy, i.e., lowering short-term interest rates. Monetary policymakers considered a variety of alternatives. Here, we focus on forward guidance as a policy option analyzed by Eggertsson and Woodford (2003) and Woodford (2012) in simple New Keynesian models. By forward guidance we mean that the monetary policymaker keeps the interest rate lower for longer than he or she ordinarily would.

As documented in Carlstrom et al. (2015), forward guidance is implausibly powerful in standard DSGE models like Christiano et al. (2005). Del Negro et al. (2012) refer to this phenomenon as the forward guidance puzzle. This puzzle has fueled an active debate. Carlstrom et al. (2015) and Kiley (2016) show that the magnitude of the forward guidance puzzle is substantially reduced in a sticky information (as opposed to a sticky price) model. Other responses to the forward guidance puzzle involve more fundamental changes, such as abandoning the representative agent framework. These changes are discussed in the next subsection. More radical responses involve abandoning strong forms of rational expectations. See for example Gabaix (2016), Woodford (2018) and Angeletos and Lian (2018).

## **5.3 Heterogeneous Agent Models**

The primary channel by which monetary-policy induced interest rate changes affect consumption in the standard New Keynesian model is by causing the representative household to reallocate consumption over time. In fact, there is a great deal of empirical micro evidence against the importance of this reallocation channel, in part because many households face binding borrowing constraints.<sup>8</sup>

Motivated by these observations, macroeconomists are exploring DSGE models where heterogeneous consumers face idiosyncratic shocks and binding borrowing constraints. Given

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<sup>8</sup> There is also important work allowing for firm heterogeneity in DSGE models. See, for example, Gilchrist et al. (2017) and Ottonello and Winberry (2017).

space constraints, we cannot review this entire body of work here. See Kaplan et al. (2017) and McKay et al. (2016) for papers that convey the flavor of the literature. Both of these papers present DSGE models in which households have uninsurable, idiosyncratic income risk. In addition, many households face borrowing constraints.<sup>9</sup>

The literature on heterogeneous agent DSGE models is still young. But it has already yielded important insights into important policy issues like the impact of forward guidance (see McKay et al. (2016) and Farhi and Werning (2017)). The literature has also led to a richer understanding of how monetary policy actions affect the economy. For example, in Kaplan et al. (2017) a monetary policy action initially affects the small set of households who actively intertemporally adjust spending in response to an interest rate change. But, most of the impact occurs through a multiplier-type process that occurs as other firms and households adjust their spending in response to the change in demand by the ‘intertemporal adjusters’. This area of research typifies the cutting edge of DSGE models: the key features are motivated by micro data and the implications (say, for the multiplier-type process) are assessed using both micro and macro data.

## 6 How are DSGE Models Used in Policy Institutions?

In this section we discuss how DSGE models are used in policy institutions. As a case study, we focus on the Board of Governors of the Federal Reserve System. We are guided in our discussion by Stanley Fischer’s description of the policy-making process at the Federal Reserve Board (see Fischer (2017)).

Before the Federal Reserve system open market committee (FOMC) meets to make policy decisions, all participants are given copies of the so-called Tealbook.<sup>10</sup> Tealbook A contains a summary and analysis of recent economic and financial developments in the United States and foreign economies as well as the Board staff’s economic forecast. The staff also provides model-based simulations of a number of alternative scenarios highlighting upside and downside risks to the baseline forecast. Examples of such scenarios include a decline in the price of oil, a rise in the value of the dollar or wage growth that is stronger than the one built into the baseline forecast. These scenarios are generated using one or more of the Board’s macroeconomic models, including the DSGE models, SIGMA and EDO.<sup>11</sup> Tealbook A also contains estimates of future outcomes in which the Federal Reserve Board uses alternative monetary policy rules as well model-based estimates of optimal monetary policy. According to Fischer (2017), DSGE models play a central, though not exclusive, role in this process. Tealbook B provides an analysis of specific policy options for the consideration of the FOMC at its meeting. According to Fischer (2017), “Typically, there are three policy alternatives - A,

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<sup>9</sup> Important earlier papers in this literature include Oh and Reis (2012), Guerrieri and Lorenzoni (2017), McKay and Reis (2016), Gornemann et al. (2016) and Auclert (2017).

<sup>10</sup> The Tealbooks are available with a five year lag at [https://www.federalreserve.gov/monetarypolicy/fomc\\_historical.htm](https://www.federalreserve.gov/monetarypolicy/fomc_historical.htm).

<sup>11</sup> For a discussion of the SIGMA and EDO models, see Erceg et al. (2006) and <https://www.federalreserve.gov/econres/edo-models-about.htm>.

B, and C - ranging from dovish to hawkish, with a centrist one in between.” The key point is that DSGE models, along with other approaches, are used to generate the quantitative implications of the specific policy alternatives considered.

The Federal Reserve System is not the only policy institution that uses DSGE models. For example, the European Central Bank, the International Monetary Fund, the Bank of Israel, the Czech National Bank, the Sveriges Riksbank, the Bank of Canada, and the Swiss National Bank all use such models in their policy process.<sup>12</sup>

We just argued that DSGE models are used to run policy simulations in various policy institutions. The results of those simulations are useful to the extent that the models are empirically plausible. One important way to assess the plausibility of a model is to consider its real time forecasting performance. Cai, Del Negro, Giannoni, Gupta, Li, and Moszkowski (2018) compare real-time forecasts of the New York Fed DSGE model with those of various private forecasters and with the median forecasts of the Federal Open Market Committee members. The DSGE model that they consider is a variant of Christiano, Motto and Rostagno (2014) that allows for shocks to the demand for government bonds. Cai et al. find that the model-based real time forecasts of inflation and output growth are comparable to that of private forecasters. Strikingly, the New York Fed DSGE model does a better job at forecasting the slow recovery than the Federal Open Market Committee, at least as judged by the root mean square errors of their median forecasts. Cai et al. argue that financial frictions play a critical role in allowing the model to anticipate the slow growth in output after the financial crisis.

In sum, DSGE models play an important role in the policymaking process. To be clear: they do not substitute for judgement, nor should they. In any event, policymakers have voted with their collective feet on the usefulness of DSGE models. In this sense, they are meeting the market test.

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<sup>12</sup> For a review of the DSGE models used in the policy process at the ECB, see Smets et al. (2010). Carabenciov et al. (2013) and Freedman et al. (2009) describe global DSGE models used for policy analysis at the International Monetary Fund (IMF), while Benes et al. (2014) describe MAPMOD, a DSGE model used at the IMF for the analysis of macroprudential policies. Clinton et al. (2017) describe the role of DSGE models in policy analysis at the Czech National Bank and Adolfson et al. (2013) describe the RAMSES II DSGE model used for policy analysis at the Sveriges Riksbank. Argov et al. (2012) describe the DSGE model used for policy analysis at the Bank of Israel, Dorich et al. (2013) describe ToTEM, the DSGE model used at the Bank of Canada for policy analysis and Alpanda et al. (2014) describe MP2, the DSGE model used at the Bank of Canada to analyze macroprudential policies. Rudolf and Zurlinden (2014) and Gerdrup et al. (2017) describe the DSGE model used at the Swiss National Bank and the Norges bank, respectively, for policy analysis.

## 7 A Brief Response to the Critics

In this section we briefly respond to some recent critiques of DSGE models. We focus on Stiglitz (2017) because his critique is well-known and representative of popular criticisms.

### *Econometric Methods*

Stiglitz claims that “Standard statistical standards are shunted aside [by DSGE modelers].” As evidence, he cites four points from what he refers to as Korinek (2017)’s “devastating critique” of DSGE practitioners. The first point is:

“...the time series employed are typically detrended using methods such as the HP filter to focus the analysis on stationary fluctuations at business cycle frequencies. Although this is useful in some applications, it risks throwing the baby out with the bathwater as many important macroeconomic phenomena are non-stationary or occur at lower frequencies.” Stiglitz (2017, page 3).

Neither Stiglitz nor Korinek offer any constructive advice on how to address the difficult problem of dealing with nonstationary data. In sharp contrast, the DSGE literature struggles mightily with this problem and adopts different strategies for modeling non-stationarity in the data. As a matter of fact, Stiglitz and Korinek’s first point is simply incorrect. The vast bulk of the modern DSGE literature does not estimate models using HP filtered data.

DSGE models of endogenous growth provide a particularly stark counterexample to Korinek and Stiglitz’s claim that modelers focus the analysis on stationary fluctuations at business cycle frequencies. See for example Comin and Gertler (2006)’s analysis of medium-term business cycles.

Second, Stiglitz reproduces Korinek (2017)’s assertion:

“... for given detrended time series, the set of moments chosen to evaluate the model and compare it to the data is largely arbitrary—there is no strong scientific basis for one particular set of moments over another”. Stiglitz (2017, page 3).

Third, Stiglitz also reproduces the following assertion by Korinek (2017):

“... for a given set of moments, there is no well-defined statistic to measure the goodness of fit of a DSGE model or to establish what constitutes an improvement in such a framework”. Stiglitz (2017, page 4).

These criticisms might have been appropriate in the 1980s. But, they simply do not apply to modern analyses, which use full information maximum likelihood or generalized method of moments.

## *Financial Frictions*

Stiglitz (2017) asserts that pre-crisis DSGE models did not allow for financial frictions or liquidity-constrained consumers. This claim is incorrect. Consider the following counter examples.

Galí et al. (2007) investigate the implications of the assumption that some consumers are liquidity constrained. Specifically, they assume that a fraction of households cannot borrow at all. They then assess how this change affects the implications of DSGE models for the effects of a shock to government consumption. Not surprisingly, they find that liquidity constraints substantially magnify the impact of government spending on GDP.

Carlstrom and Fuerst (1997) and Bernanke et al. (1999) develop DSGE models that incorporate credit market frictions which give rise a “financial accelerator” in which credit markets work to amplify and propagate shocks to the macroeconomy.

Christiano et al. (2003) add several features to the model of Christiano et al. (2005) to allow for richer financial markets. First, they incorporate the fractional reserve banking model developed by Chari et al. (1995). Second, they allow for financial frictions as modeled by Bernanke et al. (1999) and Williamson (1987). In addition, they assume that agents can only borrow using nominal non-state contingent debt, so that the model incorporates the Fisherian debt deflation channel.

Finally, we note that Iacoviello (2005) develops and estimates a DSGE model with nominal loans and collateral constraints tied to housing values. This paper is an important antecedent to the large post-crisis DSGE literature on the aggregate implications of housing market booms and busts.

Stiglitz (2017, p. 12) also writes:

“...an adequate macro model has to explain how even a moderate shock has large macroeconomic consequences.”

The post-crisis DSGE models cited in section 5.1 provide explicit counter examples to this claim.

Stiglitz (2017) also asserts that DSGE models abstract from interest rate spreads. He writes (p. 10): “...in standard models...all that matters is that somehow the central bank is able to control the interest rate. But, the interest rate is not the interest rate confronting households and firms; the spread between the two is a critical *endogenous* variable.”

Pre-crisis DSGE models like those in Williamson (1987), Carlstrom and Fuerst (1997), Chari et al. (1995) and Christiano et al. (2003) and post-crisis DSGE model like Gertler and Karadi (2011), Jermann and Quadrini (2012), Curdia and Woodford (2010) and Christiano et al. (2014) are counterexamples to Stiglitz (2017)’s assertions. In all those papers, which are only

a subset of the relevant literature, credit and the endogenous spread between the interest rates confronting households and firms play central roles.

#### *Nonlinearities and Lack of Policy Advice*

Stiglitz (2017, p. 7) writes:

“...the large DSGE models that account for some of the more realistic features of the macroeconomy can only be ‘solved’ for linear approximations and small shocks — precluding the big shocks that take us far away from the domain over which the linear approximation has validity.”

Stiglitz (2017, p. 1) also writes:

“...the inability of the DSGE model to...provide policy guidance on how to deal with the consequences [of the crisis], precipitated current dissatisfaction with the model.”

The papers cited in section 5.2 and the associated literatures are clear counterexamples to Stiglitz’s claims. So too is the simple fact that policy institutions continue to use DSGE models as part of their policy process.

#### *Heterogeneity*

Stiglitz (2017)’s critique that DSGE models do not include heterogeneous agents. He writes:

“... DSGE models seem to take it as a religious tenet that consumption should be explained by a model of a representative agent maximizing his utility over an infinite lifetime without borrowing constraints.” (Stiglitz, 2017, page 5).

This view is obviously at variance with the cutting-edge research in DSGE models (see section 5.3).

DSGE models will become better as modelers respond to informed criticism. Stiglitz’s criticisms are not informed.

## **8 Conclusion**

The DSGE enterprise is an organic process that involves the constant interaction of data and theory. Pre-crisis DSGE models had shortcomings that were highlighted by the financial crisis and its aftermath. Substantial progress has occurred since then. We have emphasized the incorporation of financial frictions and heterogeneity into DSGE models.

Because of space considerations, we have not reviewed exciting work on deviations from conventional rational expectations. These deviations include k-level thinking, robust control,

social learning, adaptive learning and relaxing the assumption of common knowledge. Frankly, we do not know which of these competing approaches will play a prominent role in the next generation of mainstream DSGE models.

Will the future generation of DSGE models predict the time and nature of the next crisis? Frankly we doubt it. As far as we know there is no sure, time-tested way of foreseeing the future. The proximate cause of the financial crisis was a profession-wide failure to observe the growing size and leverage of the shadow-banking sector. DSGE models are evolving in response to that failure as well as to the ever-growing treasure trove of micro data available to economists. We don't know yet exactly where that process will lead to. But we do know that DSGE models will remain central to how macroeconomists think about aggregate phenomena and policy. There is simply no credible alternative to policy analysis in a world of competing economic forces operating on different parts of the economy.

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## Appendix

Table 1: Priors and Posteriors of Estimated Parameters in Christiano, Eichenbaum and Trabandt (2016) Model with Calvo Sticky Wages

	Prior Distribution $\mathcal{D}, \mathbf{Mode}, [2.5-97.5\%]$	Posterior Distribution $\mathbf{Mode}, [2.5-97.5\%]$
<i>Price and Wage Setting Parameters</i>		
Calvo Price Stickiness, $\xi$	$\mathcal{B}, \mathbf{0.68}, [0.35 \ 0.89]$	$\mathbf{0.565}, [0.49 \ 0.68]$
Calvo Wage Stickiness, $\xi_w$	$\mathcal{B}, \mathbf{0.78}, [0.41 \ 0.95]$	$\mathbf{0.752}, [0.69 \ 0.76]$
Gross Price Markup, $\lambda$	$\mathcal{G}, \mathbf{1.20}, [1.06 \ 1.35]$	$\mathbf{1.181}, [1.09 \ 1.27]$
<i>Monetary Authority Parameters</i>		
Taylor Rule: Interest Rate Smoothing, $\rho_R$	$\mathcal{B}, \mathbf{0.76}, [0.22 \ 0.96]$	$\mathbf{0.796}, [0.76 \ 0.83]$
Taylor Rule: Inflation Coefficient, $r_\pi$	$\mathcal{G}, \mathbf{1.69}, [1.30 \ 2.18]$	$\mathbf{1.746}, [1.51 \ 2.06]$
Taylor Rule: GDP Gap Coefficient, $r_y$	$\mathcal{G}, \mathbf{0.08}, [0.02 \ 0.32]$	$\mathbf{0.012}, [0.00 \ 0.03]$
<i>Preferences and Technology Parameters</i>		
Consumption Habit, $b$	$\mathcal{B}, \mathbf{0.50}, [0.12 \ 0.88]$	$\mathbf{0.755}, [0.69 \ 0.78]$
Capacity Utilization Adjustment Cost, $\sigma_a$	$\mathcal{G}, \mathbf{0.32}, [0.08 \ 1.90]$	$\mathbf{0.161}, [0.05 \ 0.47]$
Investment Adjustment Cost, $S''$	$\mathcal{G}, \mathbf{3.00}, [0.74 \ 12.7]$	$\mathbf{6.507}, [4.43 \ 9.97]$
<i>Exogenous Process Parameter</i>		
Std. Deviation Monetary Policy Shock, $400\sigma_R$	$\mathcal{G}, \mathbf{0.65}, [0.51 \ 0.81]$	$\mathbf{0.673}, [0.57 \ 0.71]$

Notes: Posterior mode and parameter distributions based on a standard MCMC algorithm with a total of 1.2 million draws (8 chains with each 150,000 draws, 1/3 of draws used for burn-in, draw acceptance rates about 0.22).

$\mathcal{B}$  and  $\mathcal{G}$  denote beta and gamma distributions, respectively. Estimation of Christiano, Eichenbaum and Trabandt (2016) model with Calvo sticky wages based on Bayesian impulse response matching to a VAR monetary policy shock. See Christiano, Eichenbaum and Trabandt (2016) for details about the model and parameter notation.

Table 2: Non-Estimated Parameters and Calibrated Steady State Variables in Christiano, Eichenbaum and Trabandt (2016) Model with Calvo Sticky Wages

Parameter	Value
<i>Panel A: Parameters</i>	
Depreciation rate of physical capital, $\delta_K$	0.025
Discount factor, $\beta$	0.9968
Gross wage markup, $\lambda_w$	1.2
Inverse Frisch labor supply elasticity, $\psi$	1
Annual output per capita growth rate, $400\ln(\mu)$	1.7
Annual investment per capita growth rate, $400\ln(\mu \cdot \mu_\Psi)$	2.9
<i>Panel B: Steady State Values</i>	
Annual net inflation rate, $400(\pi - 1)$	2.5
Intermediate goods producers profits, <i>profits</i>	0
Government consumption to gross output ratio, $G/Y$	0.2

Notes: see Christiano, Eichenbaum and Trabandt (2016) for details about the model and parameter notation.

Table 3: Steady States and Implied Parameters at Estimated Posterior Mode  
in Christiano, Eichenbaum and Trabandt (2016) Model with Calvo Sticky Wages

Variable	Value
Capital to gross output ratio (quarterly), $K/Y$	6.71
Consumption to gross output ratio, $C/Y$	0.58
Investment to gross output ratio, $I/Y$	0.22
Steady state labor input, $l$	0.945
Gross nominal interest rate (quarterly), $R$	1.014
Gross real interest rate (quarterly), $R^{\text{real}}$	1.0075
Marginal cost (inverse price markup), $mc$	0.85
Capacity utilization cost parameter, $\sigma_b$	0.035
Gross output, $Y$	1.38
Real wage, $w$	1.10
Inflation target (annual percent), $\bar{\pi}$	2.5
Fixed cost to gross output ratio, $\phi/Y$	0.17

Notes: see Christiano, Eichenbaum and Trabandt (2016) for details about the model and parameter notation.